

CALCULUS AND CONSTRUCTION OF A LASER PLUG

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INTRODUCTION

The domain of the presented paper is an interdisciplinary domain. For one to make an integrated system that can ignite fuel mixtures using a laser pulse one has to unite at least two domains of the sciences: the Physics and the Mechanical Engineering.

The domain of lasers physics began once with the patenting of the first laser device (1958). After a first period, the theoretical development of the domain, a second period began where laser construction also developed. Even though laser impulse ignition systems were never used on a series production many great automotive companies are conducting studies regarding laser ignition in heat engines and we are confident that the future of these systems is not far from here. As evidence, these kind of systems already have miniature dimensions, high reliability and a low production cost.

The type of lasers developed until now presents a large spectrum of physical and operational parameters. If one categorizes laser types, then one will have lasers: with solid, liquid or gas active environment. If lasers are categorized by the length wave of the emitted radiation, then one will have: infrared lasers, visible lasers, ultraviolet lasers and X rays lasers.

The process through out atoms are lifted from one energy level to another is called pumping. Normally, this kind of process can take place in three different ways:

- optical pumping, for example, by absorbing the light emitted by a powerful lamp or another laser,
- electrical pumping, for example, by keeping the atoms (molecules) in a radio-frequency field or by injecting electrical current into an active semiconductor environment,
- chemical pumping, for example, an exothermic chemical reaction.

For an efficient pumping, the light emitted by the diode system must be transferred into an active environment in a proper manner. There are two types of pumping geometries: longitudinal pumping, where the pumping beam enters the laser environment along the resonator axis and transversal pumping, where the pumping beam is transferred in the active environment through different directions that are perpendicular to the optic resonator axis.

In the case of longitudinal pumping, the beam emitted by the laser diode has to be focalized in the active environment, in a portion of $100\ \mu\text{m} - 1\ \text{mm}$.

In the case of transversal pumping, the active environment, shaped in a bar, plate or disc shape, can be operated efficiently with at a high pumping power. There are a lot of pumping configurations but we will present two cases that are fitted best with our experiment. The first case presents a bar of Nd:YAG with the diameter of 4 mm, cooled through the use of water that runs through the tube that surrounds it, that is radially pumped by three or five modules placed into a circular arrangement. The transfer efficiency of this one is estimated at $\sim 80\%$. For one to increase the efficiency, reflectors of the pumping radiation are placed around the Nd:YAG bar, opposing the pumping diodes. This arrangement produces $\sim 600\text{W}$, output power with an optical efficiency of $\sim 25\%$. A second transversal pumping configuration is fir microchip lasers made of a composite

material called Yb:YAG/YAG. The thickness of the active environment is of 200–400 μm and it is made of a central zone made of Yb:YAG, 10 at% Yb, having the section of 2 mm \times 2 mm surrounded by undoped YAG, the total diameter being of 10 mm. The pumping radiation that is introduced through the edge of the microchip is propagated through total internal reflection in the undoped area and it is absorbed in the doped area.

THE LASER PLUG CONSTRUCTION

LASER PLUG BODY

Using the theoretically knowledge regarding the pumping diagrams, also based on the experiments previously conducted in the lab, one can now move to construct a laser plug with the dimensions similar to the one of a classical spark plug.

The functioning diagram of the experimental montage for the laser plug is presented in figure 1 and has the following composure: a Nd:YAG crystal, the S1 surface covered with an anti-reflex layer that has a transmitting coefficient of $T > 0,998$ of a length wave of $\lambda_{em} = 1064$ nm.

The S2 surface is covered with anti-reflex at 1064 nm. The Cr⁴⁺:YAG crystals used in our study have different initial transmitting coefficients, both surfaces S1 and S2 of the saturable absorbers crystals, SA are treated for anti-reflex on the length wave of $\lambda = 1064$ nm; a high reflectivity mirror HRM is placed at the entrance of the pumping wave λ_p and is focalized with a lens system L1 and L2. A second crystal with saturable absorbers, SA - Cr⁴⁺:YAG is situated near the exit of the mirrors system (OCM) or at the edge of surface S2 of the Nd:YAG crystal. Under these circumstances, the length of the resonator cannot be reduced under 60 mm.

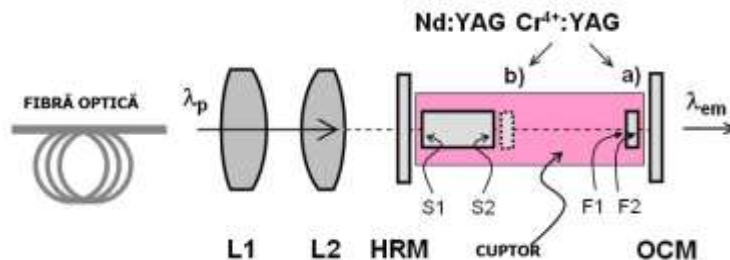


Figure 1. Functional scheme of Nd laser spark: YAG/Cr⁴⁺:YAG.

The pumping system is made of a laser diode whose radiation is coupled to a fiber optic. The end of the fiber optic is virtually coupled to the Nd:YAG crystal through an achromatic collimation system made out of the lenses L1 and L2.

The energy of the laser pulse was determined by using an energy measuring device type Laser Probe RJP-445 and the wideness of the pulse was determined using a Thorlabs SV 2 photodiode type FC with the reaction time of 0,2 ns.

The functioning of the laser plug was experimentally tested at temperatures between 25⁰C and 150⁰C, and it was concluded that the output performances of the system does not modify with the temperature. In the literature [Xiao, G., Lim, J.H., Yang, E.,

Stryland, V., Bass, M., Weichman, L., IEEE J. Quantum Electron, 1086 (1999)], are presented paper where similar pumping systems and laser emission are stable in the range of -60°C to $+90^{\circ}\text{C}$.

A constructive solution with a single-block resonator was used so that can all the mechanical adjusting components for adjusting the position of the reflecting surfaces to be eliminated (the mirrors from figure 2). Practically, a 10 mm cylindrical active environment was used with a composite structure; the active environment and the saturable absorber are glued together through high temperature optical diffusion.

The mechanical design process has as purpose to achieve a mechanical montage capable of resisting shocks and mechanical vibrations without modifying its functionality and that also can include the laser and the collimation and focalization components into a single mechanical ensemble with the maximum length of 7,62 cm.

The constructive diagram is component explode detailed in figure 2. Finally, a laser plug was obtained comparable with the sizes of a classical one, as you can see in the pictures from figure 3.

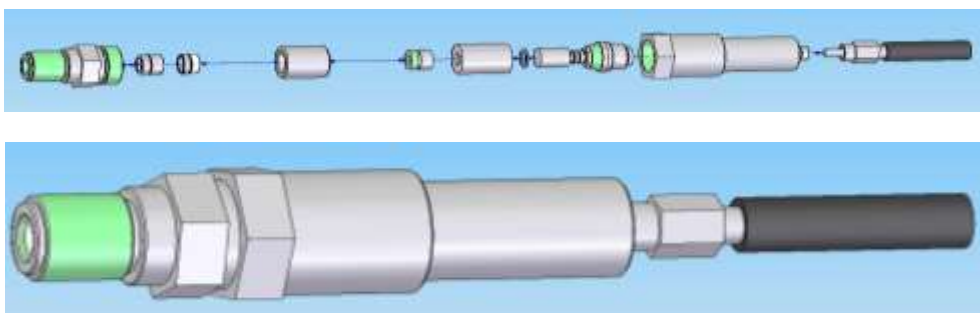


Figure 2. The constructive scheme of the laser plug.

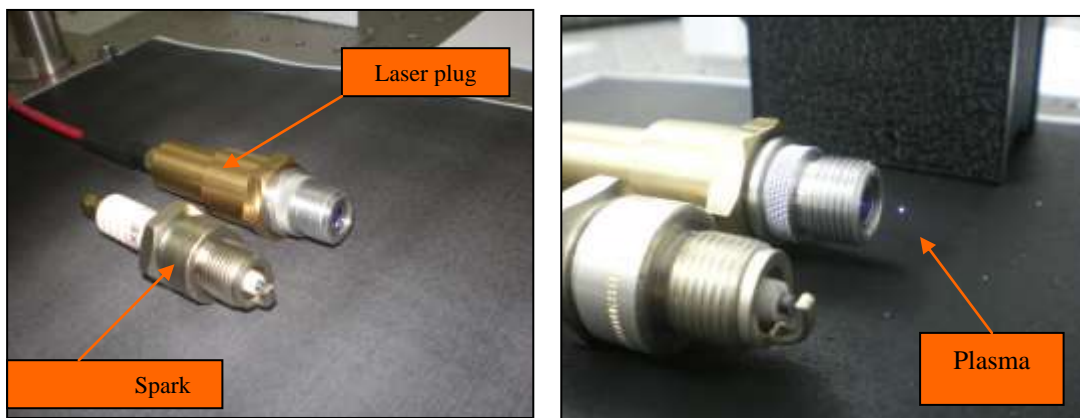


Figure 3. Dimensions of laser spark plug versus a classical electrical spark plug.

THE PUMPING SYSTEM

In figure 4 is presented the pumping and transmitting device to the plug of the pumping laser pulse. The equipments are fixed on a special laboratory surface table that

assures modularly montage procedures, according to the necessities of the experiment. All illustrations, photos, graphics, etc. must be embedded as Figures into the document. Separate graphic files are not accepted. Line art must be professionally drawn and photos must be high quality with adequate contrast.

The research must proceed with the specification of the proper characteristics for the use of equipments in the automotive domain. In figure 4 one can identify the following components: (1) the power supply of the laser diode; (2) the pumping ensemble of diodes; (3) the optical transmitting system of the laser pulse to the fiber optics; (4) fiber optics; (5) laser plug.

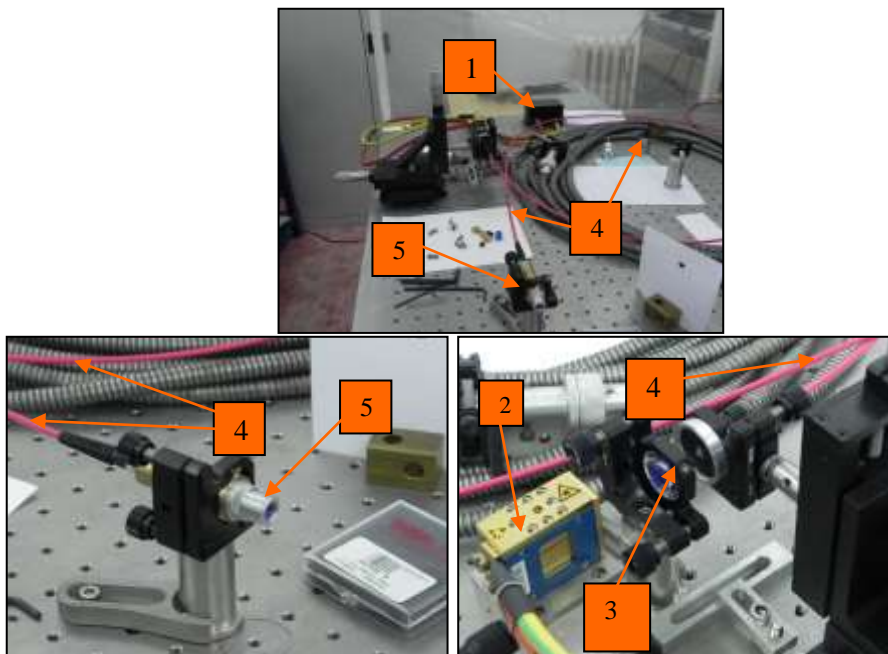


Figure 4. The components of the system of the pumping laser pulse beam.

THE UNFOLDING OF THE LASER PLUG IGITION EXPERIMENTS

GENERALITIES

In this stage of the experiments some research were conducted considering initiating the ignition of a methane-air fuel mixture having different concentrations (6%, 8%, 10% synthetic methane – air) by using the two ignition systems: a - the classical spark plug ignition; and b - the laser plug ignition.

During the experiments different parameters of the burning process were determined, such as: peak pressure, the variation of pressure through time, flame front propagation velocity, all of this conducted for different initial pressures and different values of the laser pulse energy.

Finally, one proceeds to a comparative analysis of the laser ignition with the classical spark plug ignition of the fuel mixture.

DESCRIBING THE EXPERIMENTAL BENCH

The experimental montage used for the experiments is described in figure 5 where:

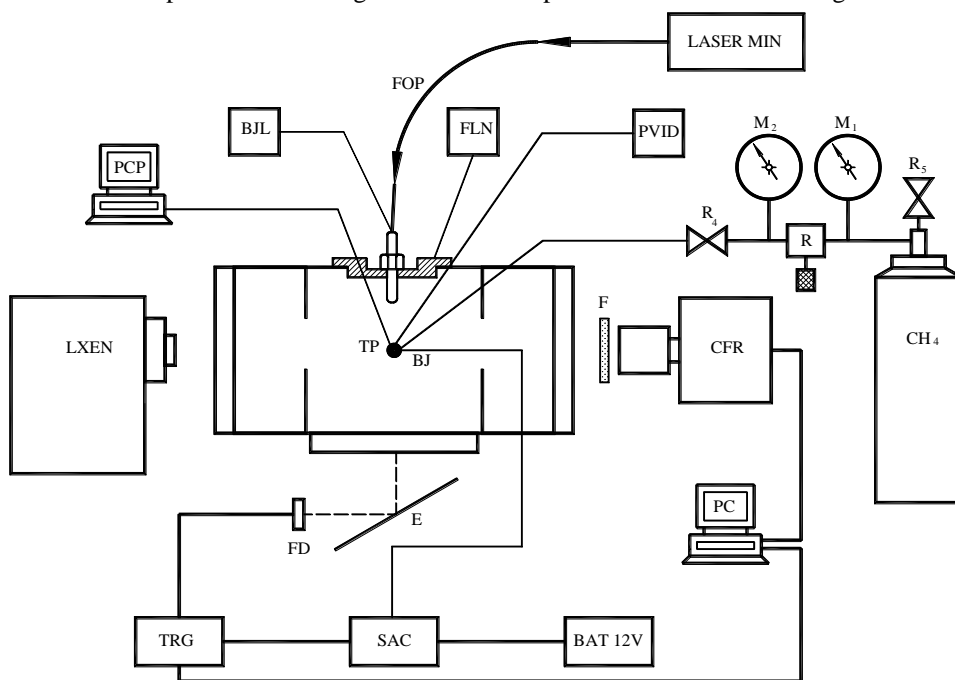


Figure 5. The scheme of the experimental bench with laser plug.

LASER MIN - is a miniature laser with a solid body Nd:YAG, pumped with laser diodes that are passively commuted with $\text{Cr}^{4+}:\text{YAG}$ ($\text{Nd}:\text{YAG}/\text{Cr}^{4+}:\text{YAG}$; BJL- is a laser spark plug that focalizes the laser pulse inside the static chamber and starts the burning process of the fuel mixture; LXEN - is a XENON lamp that assure the illumination of the burning phenomenon's from inside the chamber, in order to assure perfect view for the images recorded in shadowgraph method; FD - is the photodiode with a role of commanding the trigger system; E - is the screen for capturing the light signal, the light signal is recognized by the photodiode; CFR - is a rapid filming video camera; F - the protection filter for protecting the radiation incidence with $\lambda=1064$ nm in the camera; PC - is the computer with a software dedicated to process the images transmitted by the rapid filming video camera (CFR); FOP - is the optical fiber that transmits the laser pulse from the emitter to the plug; FLN - is the surface that assures the montage of the laser plug on the static chamber; PCP-TP - is the measuring and recording equipment for pressure variations.

The experimental bench is presented in figure 6 where: (1) is the static chamber; (2) is the rapid filming video camera; (3) is the XENON lamp; (4) - is the contrivance that assures the montage of the laser plug on the static chamber; (5) is the laser plug; (6) is the pressure regulator; (7) is the optical fiber that transmits the laser pulse from the emitter to the plug.

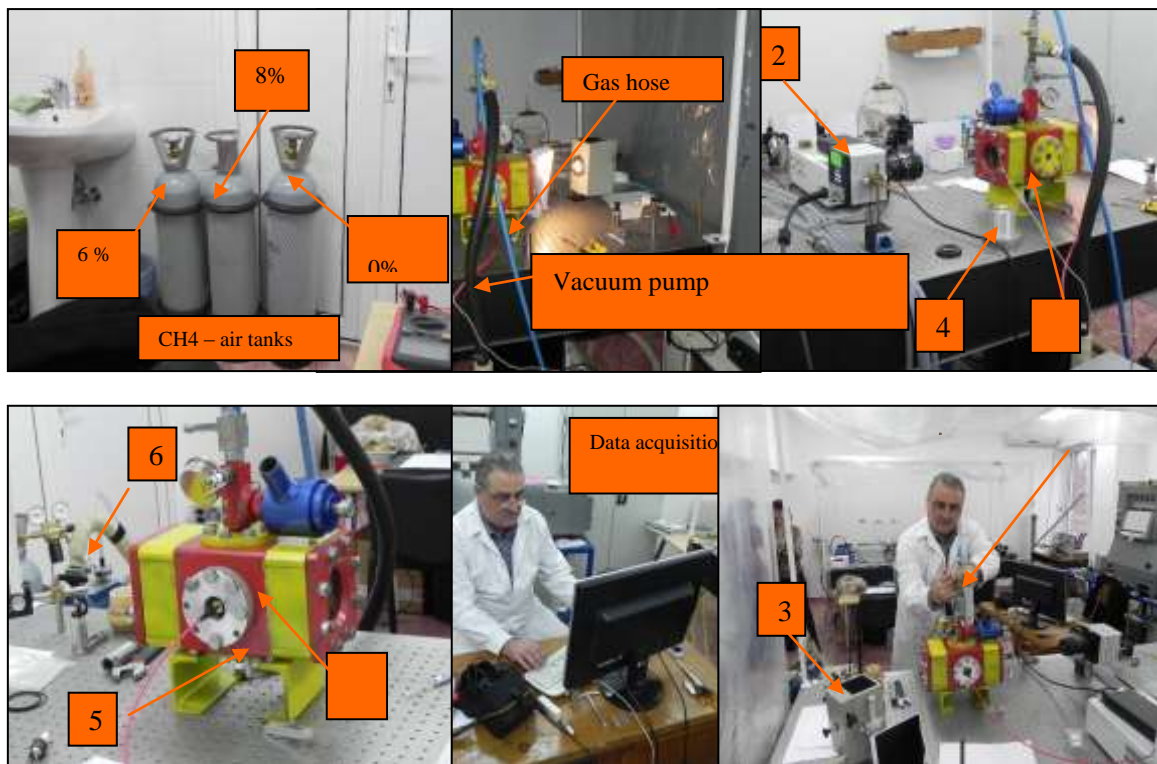


Figure 6. The physical experimental bench of the laser plug ignition system.

In order to apply the "shadowgraph" method for capturing images of the flame front propagation process, a xenon illuminating lamp was used. The Xenon lamp facilitates the illumination of the burning phenomenon's from inside the chamber, in order to assure a perfect view for the images recorded in shadowgraph method. A photodiode commands the beginning of the recording process when the burning process is initialized. The images are recorded with a rapid filming video camera type "PHOTRON – FASTCAM 1024 PCI". The recordings were taken at a velocity of 3000 frames/second at a resolution of 512 x 512 pixels. The images are captured by a data acquisition system under the form of photographs of the expanding flame front that are then processed by a PC dedicated to this kind of operation.

DESCRIBING THE EXPERIMENTAL RESULTS

Have been carried out experiments of ignition the methane-air fuel mixture burning process for three types of concentration of methane in synthetically air and for different types of initial pressure from the combustion chamber, as it is presented:

- for conventional spark plug ignition at initial pressures of 6%, 8% and 10% CH₄-air,
- for laser plug ignition at initial pressures of 6%, 8% and 10% CH₄-air.

In figures 7 and 8 are comparatively presented the flame front propagation velocity for all the experimental cases. In figure 9 are presented the photographs of the flame front

evolution for the methane-air concentrations: 8% concentration - $P_i = 5$ bar, 8% concentration - $P_i = 5,5$ bar, laser ignition.

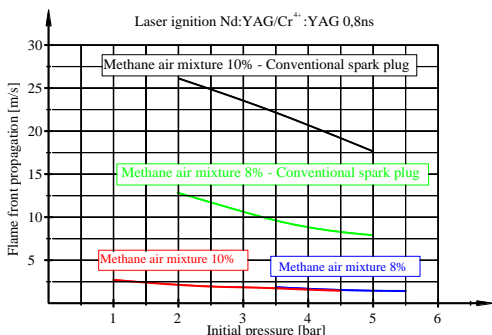


Figure 7. The flame front velocity variation depending on the initial pressure of the comparative fuel mixture - ignited with conventional and laser plug.

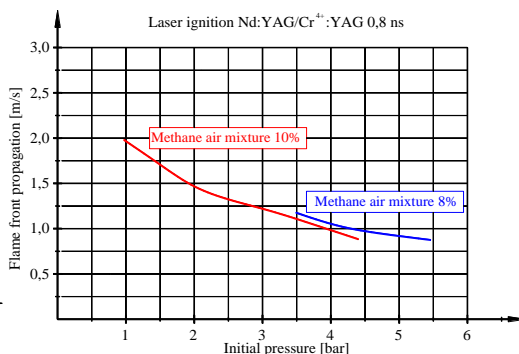


Figure 8. The flame front velocity variation depending on the initial pressure of the fuel mixture, in the case of laser ignition.

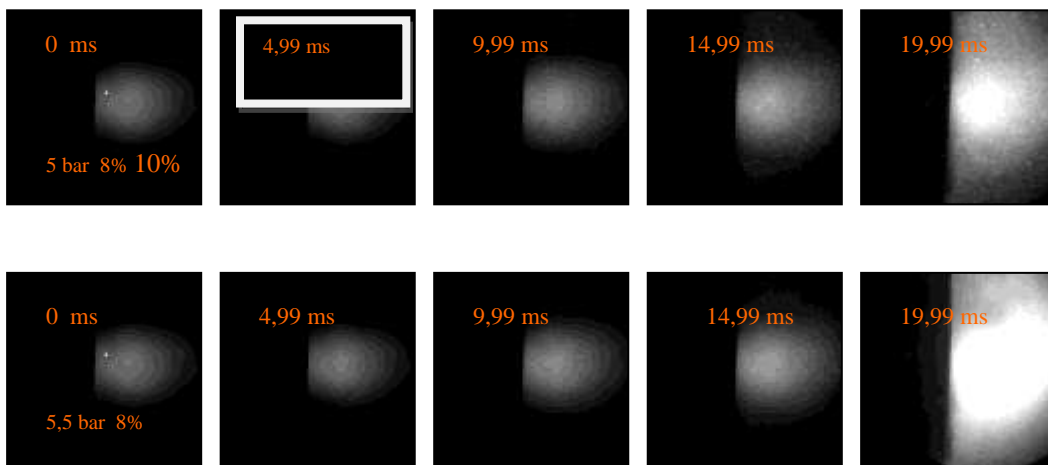


Figure 9. The evolution through time of the flame front for the methane-air mixture with the following characteristics: 8% concentration - $P_i = 5$ bar; 8% concentration - $P_i = 5,5$ bar ; laser ignition.

In figure 10 one presents the evolution of the flame front propagation for the methane-air fuel mixture with the following concentrations: 8% concentration - $P_i = 4$ bar; 8% concentration - $P_i = 5,5$ bar ; conventional electrical plug ignition.

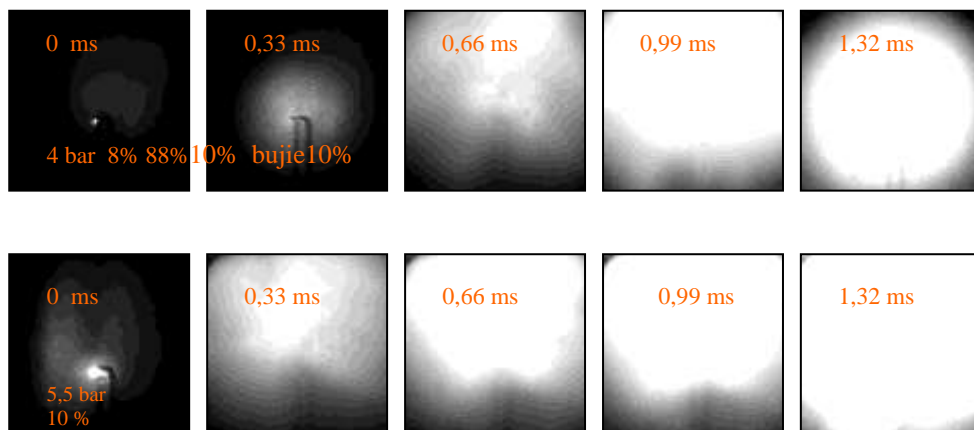


Figure 10. The evolution of the flame front propagation for the methane-air fuel mixture with the following concentrations: 8% concentration - $P_i = 4 \text{ bar}$; 8% concentration - $P_i = 5.5 \text{ bar}$; electrical spark ignition.

In figure 11 it is presented the graph that describes the maximum pressure variation that is obtained in the combustion chamber depending on the initial pressure for a fuel mixture of 8% methane-air.

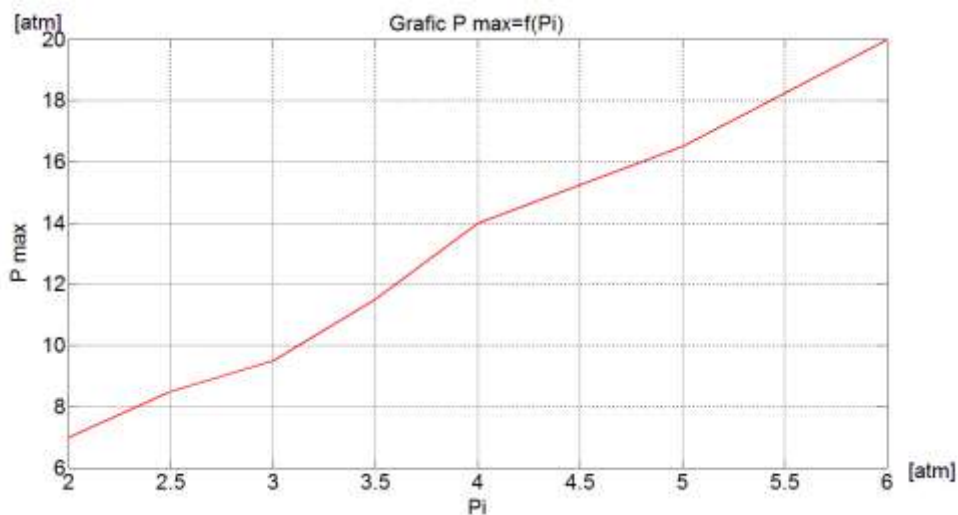


Figure 11. Maximum pressure evolution depending on the initial pressure.

CONCLUSIONS THAT RESULTED FROM THE EXPERIMENTS

From the experiments conducted in this stage of the research one concluded the following things: the laser plug type Nd:YAG/Cr4+:YAG, having the characteristics: 1ns pulse duration, pulse frequency of 5 Hz, the energy of 3 mJ, the wavelength of $\lambda = 1064$

nm, can ignite methane-air fuel mixtures for different concentrations and initial pressures in the combustion chamber.

It was proven experimentally that the ensemble laser emitter - laser plug is stable at temperatures in the range of -60° to $+150^{\circ}\text{C}$.

The laser pulse emission equipment can be made at real sizes, so it could be mounted on a vehicle, without any technical difficulties.

The laser plug can be made out of a case identical with the one of a spark plug so that it can be mounted on the engine without any other modifications.

The fiber optics permits the laser pulse to be transmitted from the emission equipment to the laser plug, on any distance, just by avoiding the accentuated angularly strangling condition. As a result, the emission equipment can be mounted inside the vehicle from where the laser pulse can be transmitted through fiber optics to the laser plugs mounted on the engine, without any other technical difficulties or special ensembles.

After a relatively small number of pulses the lenses from inside the chamber are covered with smoke, process that diminishes the energy of the discharge pulse. Solving this inconvenient represents a major research direction that will shape the future of the laser plugs on the internal combustion engines from the product series.

The conducted experiments proves the opportunity for creating and perfecting laser equipments that could be tested in real functioning conditions, on an engine and on a vehicle.

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